Research and Development Laboratories
of the
Portland Cement Association

RESEARCH DEPARTMENT

BULLETIN 91

Early High-Strength Concrete for Prestressing

BY

PAUL KLIEGER

MARCH, 1958

CHICAGO

Authorized Reprint from
PROCEEDINGS, WORLD CONFERENCE ON PRESTRESSED CONCRETE
SAN FRANCISCO, CALIFORNIA
July, 1957

EARLY HIGH-STRENGTH CONCRETE FOR PRESTRESSING

Paul Klieger*

SYNOPSIS

The continued growth of prestressed concrete depends to a large extent on its relative economy in comparison with other structural materials. The cost of producing high-strength concrete and the resulting economies which can be effected by early application of prestress are important factors in this economic picture.

This report discusses the techniques which are presently at our disposal for producing early high-strength concrete. Data on other properties of high-strength concrete, such as elasticity, creep, drying shrinkage, bond to steel, and durability are presented.

INTRODUCTION

The use of prestressed concrete is growing rapidly. Continued growth is dependent to a large extent on its relative economy and suitability in comparison with other structural materials.

Two important factors in the economics of prestressed concrete are the cost of producing early high-strength concrete and the resulting economies which can be effected by the early application of the prestress in either the pretensioned or post-tensioned methods. In the pretensioned method, early application of prestress permits more efficient utilization of forms and stressing equipment. The earlier the concrete reaches the required strength, the earlier the prestress can be applied.

This report deals with the means which are presently at our disposal for producing early high-strength concrete. The choice of method for a particular situation will depend upon the availability of specific materials, mixing equipment, and compacting equipment and on the relative effectiveness of the method. When considering these means for attaining early high strength, important physical properties of the concrete other than strength must also be kept in mind.

FUNDAMENTAL BASIS OF STRENGTH DEVELOPMENT

The cementing medium in concrete is produced by the chemical reaction between portland cement and water. The inherent strength of this medium is primarily a function of the ratio of the amounts of these two components, normally expressed either on a weight basis or in gallons per sack of cement. This is the familiar "water - cement ratio". The manner in which this ratio influences the strength of the paste or gel, and hence the strength of the concrete, is illustrated in Fig. 1. The solid-line curve is the familiar characterization of Abram's water-cement ratio law for "..... plastic, workable mixes .....," or as we now realize for mixes fully compacted (minimum entrapped air voids). Actually, this particular example represents the relationship between water-cement ratio and strength for an initially workable mix of fixed proportions. As the water-cement ratio of the mix is decreased, by decreasing the amount of water added, the mix becomes progressively less workable and full compaction by hand-placing methods becomes impossible, as indicated by the drop in strength when the water-cement ratio is decreased below a point characteristic of each particular mix. If at this point mechanical compaction is used, the strengths will continue to increase until the particular method of mechanical compaction being used no longer produces full compaction.

For fully compacted concrete, therefore, the strength is determined primarily by the water-cement ratio of the paste. The proportion of the potential or ultimate strength actually developed in a given concrete at a particular age is affected by many factors such as curing conditions, type of cement, and others.

INFLUENCE OF MIX PROPORTIONS

The amount of a given aggregate that can be accommodated in a cement paste of a particular water-cement ratio depends upon its influence on the workability of the resulting mixture. The limiting amount is that maximum amount which can be used and still attain full compaction of the concrete. In other words, the mix proportions (meaning the relative proportions of cement and aggregate) are of importance mainly insofar as they influence the workability of the concrete.

Increasing the proportion of aggregate in a mix with a fixed water-cement ratio progressively decreases the consistency and workability of the concrete. There are a number of advantages to using the maximum amount of aggregate per unit of cement consistent with available placing techniques. Some of these advantages relative to certain physical properties of the resulting

*Senior Research Engineer, Applied Research Section, Portland Cement Association, Chicago.

concrete will be discussed later in this report. Of main interest, however, is the influence of mix proportions on the cement requirement of the concrete. An increase in the amount of aggregate per unit volume in a mix of fixed water-cement ratio results in a reduction in both the amount of cement and the amount of water per unit volume of concrete produced and therefore a more economical concrete with lower shrinkage characteristics. Considerably more economy, in addition to other benefits, can be effected by utilizing a more efficient placing technique, such as vibration, in order to use still greater amounts of aggregate. Fig. 2 shows some data obtained recently in our laboratory using a Type I portland cement in concretes having net water-cement ratios ranging from 0.29 to 0.41 by weight. The hand-placed concretes required considerably more paste per unit volume in order to provide sufficient workability to enable compaction with relative ease. The cement contents of these hand-placed mixes ranged from 6 to 12 sacks per cubic yard. The concretes which were placed by external vibration, however, contained less paste per unit volume and though they were dry and unworkable by hand-placing standards, these concretes were easily compacted by this external vibration. The cement contents of these vibrated concretes ranged from 5 to 9½ sacks per cubic yard. The reductions in cement content afforded by a change in mix proportions and a concomitant change in placing technique ranged from 1 to 2½ sacks per cubic yard. The net saving effected by these reductions in cement content would depend upon additional costs which might be incurred in mixing these dry concretes, transporting and vibrating, and the cost of more substantial forms required for vibration.

One other aspect of mix proportions is the proportion of sand in the total aggregate. Progressing from a hand-placing technique to more and more efficient methods of mechanical compaction, the amount of sand required for good placeability can be reduced materially. This reduction in sand percentage permits the use of less water per cubic yard for the same level of workability and consequently a greater amount of aggregate per unit of cement. The vibrated mixes had lower sand percentages than the hand-placed mixes, as shown in Fig. 2.

INFLUENCE OF CURING CONDITIONS

Since the reaction between cement and water is chemical, the temperature at which the reaction takes place would be expected to influence the rate of the reaction. Both the availability of water and the temperature are extremely important aspects of curing, particularly with regard to early high-strength development. For prestressing, the time required to develop the necessary strength is of particular importance.

Availability of Water

When cement and water react, an internal deficiency of water in the system may occur unless additional curing water is supplied(1). If this deficiency (by self-desiccation) occurs, the rate and degree of ultimate hydration may be reduced. Such deficiencies are more likely to occur in low water-cement ratio mixes for prestressed concrete.

The influence of this factor on strength development is greater at the later ages than it is at the age of one day. This effect is illustrated in Figs. 3 and 4. Fig. 3 shows data for hand-placed concretes (1 to 2 in. slump) where the availability of curing water during the 24-hr. period in which the test cylinders were in the molds was increased by two means, (1) saturating the aggregate prior to use, and (2) ponding the top of the cylinder immediately after casting. For the 0.42 water-cement ratio concrete the increase in strength due to these techniques was nil at one day and about 750 psi at 28 days. For the 0.29 water-cement ratio concrete the increase was about 400 psi at one day and 850 psi at 28 days. Fig. 4 shows data for vibrated concretes (zero slump) made with saturated aggregate with either damp burlap covering or ponding during the 24-hr. period in the molds. At one day, there was little influence of the ponding, the increases ranging from zero at 0.42 water-cement ratio to about 150 psi at 0.29 water-cement ratio. At 28 days, there was no increase at 0.42 and about 1000 psi increase at 0.29 water-cement ratio. These increases at the low water-cement ratio become significant as early as three days, as can be seen in Fig. 4. The influence of depth of section on the efficiency of the ponding technique has not yet been evaluated. Burlap in direct contact with the surface and kept saturated would approximate the ponding treatment.

For concrete made with lightweight aggregates (2), tests indicate that ponding was of no benefit. Lightweight aggregates absorb considerable water during mixing which apparently can transfer to the paste during hydration.

Temperature

Since the reaction between water and cement is a chemical reaction, increasing the temperature during curing might be expected to increase the rate of strength gain. To illustrate the influence of temperature on

strength development, Fig. 5 shows the one-day strengths of concretes mixed and cured at different temperatures[3] as percentages of the 73°F strengths. These concretes were cast in uninsulated steel molds and were stored at the temperatures indicated. Temperatures below 73°F resulted in lower one-day strengths, and temperatures above 73°F resulted in higher one-day strengths, than that developed at 73°F. Although later-age strengths are somewhat reduced by initial curing at elevated temperatures, no retrogression in strength occurs with age [3].

Acceleration of strength gain at the early ages by providing elevated temperatures can be accomplished in a number of ways. The use of saturated steam at atmospheric pressure serves up to the boiling point of water. From that point, saturated steam under pressure can be used to provide still higher temperatures. For the prestressed concrete industry, saturated steam at atmospheric pressure appears most adaptable for the size, shape, and manner in which the majority of units must be made. Ponding of exposed top surfaces or covering with burlap kept saturated could be employed to advantage to reduce the possibility of drying and to provide additional curing water to counter the effect of self-dessication. Saturated steam must be provided to prevent drying out during the curing process. This type of curing normally employs temperatures in the range of 140 to 165°F. Temperatures higher than this may, in some cases, result in somewhat lower strengths at the end of the curing cycle. This range appears to be the optimum for most concretes. The cycle usually consists of a 3 to 6-hour preset, or waiting, period immediately after fabrication at normal temperature, followed by about a 16-hour period of heating with saturated steam at the temperature within the range selected as optimum for the materials being used, and subsequent gradual cooling over about a 3-hour period to avoid excessive drying. The optimum temperature is dependent to some extent on mix proportions, type of cement, and type of aggregate. In a recent series of tests, concretes were prepared at 0.4 and 0.5 water-cement ratios by weight, cement contents approximately 9½ and 7½ sacks of Type I portland cement, respectively, and subjected to saturated steam at 140°F for 16 hours after a 4-hour preset period at 73°F. The one-day strength of these concretes was 4080 and 2940 psi, respectively, in contrast to the respective 73°F one-day strengths of 1590 and 950 psi. This comparison demonstrates the strength increases that can be obtained by the use of saturated-steam curing at atmospheric pressure.

The reaction between cement and water liberates heat. In the production of prestressed concrete elements mixes of low water-cement ratio and high cement content are necessarily employed. Because of the high concentration of cement in these mixes, a considerable amount of heat is liberated. This heat, if retained, can raise the concrete temperature by a substantial amount and thereby increase early strength development. Figure 6 shows the increase in concrete temperature normally to be expected if the heat generated were fully retained. These theoretical calculations were based on heat-of-hydration studies of neat-cement pastes using the conduction-calorimeter technique[4] and are for a 4½ gal. per sk. mix containing 8½ sk. of Type I or Type III portland cement per cu. yd. For example, using a typical Type I cement in this concrete mix at 70°F, and retaining all of the heat generated, a rise of almost 60°F in concrete temperature to about 130°F at 24 hours should be noted. Actually, the temperature would rise somewhat above 130°F, since the additional heat increases the rate of hydration and more and more heat would be generated as the concrete temperature rose, as seen by the 105°F data for both types of cement. Complete retention of the heat generated within the first 24 hours could raise the temperature of the concrete well over what might be considered optimum. However, almost perfect insulation would be extremely costly and is not likely to be used. Insulation of the blanket or bat type, such as spun glass, rock wool, balsam wool, and others, is reusable and can retain sufficient heat to provide significant increases in the early strengths. Insulation used in combination with some artificial heat at the start to promote heat generation appears to offer possible economies in the production of prestressed units.

The effectiveness of various insulating materials is being evaluated in a current series of tests in our laboratory. As an example, concrete cylinders were fabricated by external vibration in steel molds, using a dry mix at a water-cement ratio of 0.36 by weight and both Type I and Type III portland cements. The tops of the cylinders were sealed with a thin sheet of plastic to prevent loss of moisture. The group of molds was then completely wrapped in a one-inch-thick blanket of spun glass fibers. After one day, some of the cylinders were removed for immediate testing or for 2 days of additional curing in the moistroom at 73°F. The remainder were kept wrapped for an additional two days. The results of these strength tests are shown in Fig. 7. The one-day strength was increased from 2200 psi to 2700 psi for the Type I cement, an increase of about 25%. For the Type III cement, the increase was about 28%. The temperature of the concrete at the end of the first day was about 90°F for the Type I cement and about 100°F for the Type III cement. The initial temperature of both concretes was about 75°F. Actually, for complete

retention of heat, these temperatures at one day should have been somewhat higher. Under these test conditions, this particular mode of insulation retained about 40% of the heat generated. Nevertheless, the increase in the one-day strength was 23% for the Type I cement and 28% for the Type III cement -- economically significant increases considering that the insulation can be reused a number of times. Maintaining insulation for 3 days resulted in further increases in strength. The cost of more efficient insulation, which would retain a greater proportion of the heat generated, would have to be balanced against the cost of supplying additional heat by means of saturated steam or other means. A combination of these two techniques appears to be the most desirable course, particularly since some insulating enclosure must be provided even when additional heat is supplied. More efficient, reusable insulation would result in savings in the amounts of additional heat which would need to be provided.

INFLUENCE OF TYPE OF CEMENT

The rate of strength development of concrete can be varied by using different types of portland cement. Of the different types in general use (ASTM Types I, II, III, and their counterpart air-entraining cements), ASTM Type III (high-early-strength portland cement) develops strength more rapidly than the other types. Concrete made with this type of cement gains strength more rapidly at early ages than concrete made with Type I or Type II cement. However, under continuous moist curing the strengths are about the same at ages later than about 3 months. Figure 8 shows some typical strength data of concretes made with Type I and Type III portland cements. The net water-cement ratio of these concretes was 0.35 by weight, the cement content $6\frac{1}{2}$ sk. per cu. yd. These were zero-slump concretes compacted by external vibration. Curing was at 73^{o}F, in steel molds for the first day and thereafter in the moistroom. The concretes made with the Type III cement were considerably stronger than those made with the Type I cement; the strength ratios of Type III to Type I were 1.86, 1.50, and 1.23 for 1, 3, and 7 days, respectively. The use of Type III cement coupled with the blanket insulation previously described and saturated-steam curing at elevated temperature would produce concretes having a one-day strength well in excess of 5000 psi.

THE INFLUENCE OF ACCELERATORS

The hydration of cement can be accelerated by the addition of relatively small amounts of inorganic materials. Of these materials, calcium chloride is the most commonly used accelerator.

Calcium chloride in amounts ranging from one to two percent by weight of the cement provides significant increases in early strength development In common with other means of accelerating strengtn gain at the early ages, at 28 days and later the strengths of concretes with and without calcium chloride are approximately equal. Figure 9 shows the effect of 2% of calcium chloride on the strength of a 0.35 water-cement ratio mix made with Type I portland cement. There is a considerable increase in the one-day strengths, these increases decreasing with age, as indicated by the ratios at the ages of one, three, and seven days.

However, a serious problem has arisen with regard to the use of calcium chloride in prestressed concrete. The presence of chloride ions in the concrete may produce conditions favorable for corrosion of the steel. Localized and severe corrosion under these conditions may occur in the steel, particularly at voids in the interface between the steel and the concrete, causing steel failure. A comprehensive study of this corrosion problem is now under way in our laboratories. Available evidence indicates only that when chloride ions are present, localized corrosion and consequent failure of steel under stress may take place. At present, the use of calcium chloride for prestressed concrete is not recommended, particularly for pretensioned prestressed applications. In post-tensioned work, either grouting of the steel after tensioning or the presence of a bond-breaking shield might introduce a sufficient barrier to chloride ions. This possibility is being investigated.

INFLUENCE OF COMPACTION

It was stated earlier in this report that the strength of the concrete was controlled primarily by the water-cement ratio, provided the concrete was fully compacted. Actually, strength is related to the voids-cement ratio, the voids being the sum of the volumes of water and air in the concrete, the volume of air being an index of the efficiency of compaction. The air in this case is not the air which we intentionally entrain in the paste by means of air-entraining cements or air-entraining admixtures, but is entrapped air resulting from the use of dry, harsh mixes.

Any technique of compaction is suitable, provided full compaction can be attained. If full compaction is attained, the water-cement ratio will then be as good a criterion of strength as voids-cement ratio, since the amount of entrapped air voids would be small and exert little influence on the magnitude of the voids-cement ratio. Figure 10 shows the one-day and three-day strengths

of concretes of four different water-cement ratios, for both hand-placed and vibrated concretes. Essentially similar strengths were produced by the two placing techniques. However, the hand-placed concretes had slumps in the range of one to two inches and were easily compacted by rodding. In a recent series of tests of zero-slump concrete by both hand-placing and vibration, the strength ratios of vibrated to hand-placed concrete ranged from 1.00 to 1.09 for about a 5% average increase in strength of the vibrated concretes. This indicates that with the dry, harsh mixes, hand-rodding of the specimens did not achieve complete compaction, even though extreme care was taken.

In stiff, low water-cement ratio mixes, mechanical compaction must be resorted to in order to compact these mixes efficiently and economically. Figure 2 showed the economy which could be effected by the use of vibration in compacting these concretes. Three general types of vibration may be employed: internal, form, or surface vibration. Internal and form vibration are more generally applicable to the production of prestressed concrete units. Of these two methods, internal vibration is to be preferred since the power is transmitted directly to the concrete and the portability of the equipment permits more flexible use during vibration.

Opinions vary as to the influence of frequency of vibration and amplitude of vibration on strength. A recent series of tests were made in our laboratory using a vibrating table to supply external vibration during casting of test cylinders. Aside from the time of vibration necessary, there appeared to be little choice as to frequency or amplitude provided that the concrete was fully compacted. Some typical test results are shown in Fig. 11. Frequencies ranging from 3600 to 11,000 vibrations per minute used in combination with different amplitude settings showed no consistent influence on the strengths of these zero-slump concretes. However, frequency and amplitude influenced considerably the duration of vibration necessary to achieve adequate compaction. At a particular frequency, a larger amplitude of vibration reduced the required time and, at a given amplitude, a higher frequency reduced the time for compaction. Obviously, from the standpoint of economy, the particular combination of frequency and amplitude which achieves full compaction in the shortest time would be desirable. To take advantage of this situation would necessitate costly variable frequency, variable amplitude vibrating equipment. Equipment generally available, at least for internal vibration, is of the fixed-frequency type, with little opportunity for amplitude change. The choice of vibration equipment for a particular application cannot readily be determined by theoretical analyses. The influence of factors such as frequency, amplitude, mix characteristics, and size and shape of member is difficult to evaluate. The type of equipment required is generally determined by trial.

A means for producing low water-cement ratio concrete is available in the patented vacuum-treatment process. This method of extracting water from plastic mixes is limited to the use of relatively thin sections.

INFLUENCE OF AGGREGATE CHARACTERISTICS

Since aggregate comprises a large fraction of the volume of concrete, the characteristics of the aggregate significantly influence the properties of the concrete. Of immediate interest is the influence of these characteristics on strength.

Grading and maximum size of aggregate affect strength only indirectly by their influence on the water requirements for a particular level of consistency. For the same water-cement ratios, different gradations of the same aggregate will produce essentially the same strengths. A grading which requires more water for a particular level of workability will, however, result necessarily in a higher cement content in a mix of fixed water-cement ratio. A decrease in the maximum size of aggregate also results in higher water requirement with its consequent influence on cement content. Generally, once a mix is selected, control is governed by the consistency of the concrete produced. Variations which occur in grading would then be reflected in different amounts of water necessary to attain the desired consistency. This would result in changes in water-cement ratio and concomitant changes in strength. These variations in strength, if not reduced by closer control of uniformity of grading, would require a redesign of the mix in order to insure the production of satisfactory minimum strengths. This would result in more costly concrete. Separation of the aggregate into a number of size fractions and recombining when batching would increase the uniformity of concrete produced. On sizable jobs, sufficient savings would result from increased uniformity of concrete to more than offset the cost of processing the aggregates. More emphasis should be placed on uniformity of grading of the fine aggregate, since variations in grading of the fine aggregate influence workability to a greater degree than variations in grading of the coarse aggregate.

Particle shape exerts an influence mainly on the amount of paste necessary to achieve workability. Flat and elongated particles require a greater paste content than rounded or cubical particles for the same workability. Significant savings in concrete costs can be effected by reducing flat and elongated pieces to a minimum.

In the case of aggregate manufactured by crushing, particles more nearly cubical are to be preferred over angular particles, the shape being generally dependent on the type of crusher being used.

Different types of aggregates may, at equal water-cement ratios, produce concretes of different strength. Some of this difference may result indirectly from the effect of certain aggregate characteristics such as surface texture on the amount of cement paste in the mix. Smooth surfaces require less paste for lubrication than rough surfaces. The main differences in strength attributable to aggregate type are thought to be due to the degree of bond developed between the paste and aggregate (both porosity and surface texture being important) and to the strength and elastic properties of the aggregate particles themselves. The interplay of characteristics such as porosity, surface texture, strength, elastic properties, and other variables makes it difficult to predict behavior. Bond of the paste to aggregate particles generally increases with roughness, although many other aggregate characteristics also influence bond. Increase in bond due to surface roughness, or for any other reason, will increase the flexural strength of the concrete. However, differences in surface texture have relatively little influence on compressive strength.

Lightweight Aggregates

Lightweight aggregate, generally produced by artificial means, is assuming increasing importance in prestressed concrete work, and, for that matter, in most phases of concrete construction. These aggregates are obtained by expanding, calcining, or sintering materials such as blast-furnace slag, shale, slate, clay, diatomite, and others. Differences in the elastic properties of lightweight aggregate can cause more change in strength and elasticity of the concrete than those of the heavier natural aggregates such as gravels and crushed stones. Although, like normal-weight concrete, water-cement ratio is the main controlling influence in strength development, an important factor is the strength of the particles of lightweight aggregate.

One of the reasons for the apparent wide differences in strengths produced by different lightweight aggregates lies in the large and not readily determinable absorption characteristics of these materials. For this reason, mixes are usually compared on an equal cement-content basis, rather than on an equal water-cement ratio basis. This may account for a large part of the strength differences attributed to the aggregate, per se. Lightweight-aggregate concretes differ considerably in the amount of water required to attain proper workability, due to grading, shape, and surface texture of the aggregate used. Those aggregates which, for the reasons noted, require excessive amounts of water to produce proper workability will therefore require excessive amounts of cement in order to provide adequare strength. The use of natural sand to replace a portion of the fines or the use of air entrainment will result in reduced water requirements. The natural sand will raise the unit weight of the concrete and decrease the advantages accruing to lower weight.

Concrete made with lightweight aggregate has generally been said to have an upper limit of compressive strength of about 5000 psi. Advances in the technology of manufacture of such aggregates, closer control of uniformity of grading, and a greater appreciation of proportioning and mixing techniques have served to raise this limit considerably. Early high-strength concrete can be produced with most lightweight aggregates in a manner similar to the heavier natural gravels and crushed stones. Some work by our laboratories in this regard will appear this year in the Journal of the American Concrete Institute (2).

INFLUENCE OF CONTROL OF UNIFORMITY

When representative samples of a concrete are subjected to strength tests, the results of these tests show a certain dispersion about an arithmetic mean. This is not a peculiarity of concrete alone, but is a common occurrence with other building materials. These differences in strength of presumably representative test cylinders made from supposedly like batches of concrete may result from either random or systematic variation of numerous factors. A few, for example, are variations in batching and mixing, curing of cylinders, sampling of concrete, compaction, and capping and testing techniques.

The degree to which effective control measures are adhered to in minimizing variations determines the magnitude of the spread or dispersion of test results about the arithmetic mean. In order to assure that more than a certain small percentage of the concrete being produced does not go below a specified minimum design strength, the average strength must of necessity be higher than this minimum. The difference between this average strength and the minimum is influenced by the degree of control of all phases of concrete making, sampling, curing, and testing. The less effective the control exercised, the higher the average strength required to ensure attaining the proper percentage of tests higher than the minimum design strength designated. When producing early high-strength concrete for prestressing, designing for a considerably higher strength than required in order to offset poor control is particularly uneconomical.

The level of control required for prestressed concrete work should be higher than that for most other con-

crete construction. ACI Committee 214[5] recommends for most concrete construction that the control of concrete-making operations be such that not more than one test in ten fall below the designated minimum strength. For prestressed concrete work a higher degree of control appears desirable, possibly as a goal one test out of one hundred. In order to attain this goal as economically as possible and not need to over-design the concrete drastically to attain the requirement of one in one hundred, strict attention must be paid to all phases of the operation to reduce variations to a minimum. The lower the coefficient of variation of test results, regardless of the probability level adopted, the lower the average strength required to assure attaining the necessary minimum strength of concrete. For example, considering the criterion of one test out of one hundred falling below a designated minimum strength, with a coefficient of variation of 10% (considered excellent for general field construction), the average concrete strength necessary would be about 31% higher than this minimum. For a coefficient of variation of 5%, the average concrete strength necessary would be only 14% higher than the minimum strength. The savings in concrete cost would help offset any additional costs incident to closer control of operations.

OTHER PROPERTIES OF EARLY HIGH-STRENGTH CONCRETE

In the design of prestressed concrete units, physical properties of concrete aside from strength are also of importance. Properties such as modulus of elasticity, creep, drying shrinkage, bond to steel, and durability under various conditions of exposure must also be considered. Considerable information relative to these properties is available for concretes of all types used in varied structural applications. Most of this information has been obtained for concrete strengths ranging up to 5000 or 6000 psi. The increasing emphasis on early high-strength concrete is pointing up the need for more data concerning these properties. Data obtained in some of our recently completed laboratory studies and current studies afford additional background for the discussion to follow.

Modulus of Elasticity

The modulus of elasticity of concrete depends upon the modulus of the cement paste, the modulus of the aggregate, and the relative amounts of these two components. The modulus of elasticity of the paste component increases as the degree of hydration increases. Changes in modulus for a given concrete occur because of changes in the modulus of elasticity of the paste as curing continues. As the modulus of the paste increases, the concrete strength also increases, and for any given concrete mixture and curing condition there then exists a general empirical relationship between strength and modulus of elasticity. For the same cement and aggregate, this empirical relationship between strength and modulus is influenced by the relative amounts of paste and aggregate[7]. The moduli of elasticity of pastes range up to 2.5 to 3.5×10^6 psi, while those for aggregates are generally considerably higher, except for most of the lightweight aggregates. Therefore, the greater the volume of paste per unit of aggregate, the lower the modulus of elasticity should be at comparable degrees of hydration or strength. Data supporting this are shown in Fig. 12. Here we see the influence of the volumetric ratio of paste to aggregate on the modulus of elasticity for different levels of compressive strength. This merely emphasizes the fact that strength, by itself, is not a good indicator of modulus of elasticity of different concrete mixtures over the whole range of strengths possible to produce with the same materials used in different proportions. What is important is how the strength was obtained for any given set of materials. Was it by longer curing, by a change in mix proportions, or by a change in water-cement ratio? However, for any particular mix strength serves as a good indicator of the modulus of elasticity, the modulus increasing with strength. The modulus does not increase as rapidly as strength and appears to approach some limiting value in the high-strength region.

The modulus of elasticity of concretes made with lightweight aggregates is not influenced materially by the volumetric concentration of aggregate since the modulus of the aggregate is generally of the same order of magnitude as that of the paste[2]. The modulus of elasticity of concretes made with lightweight aggregate is considerably lower than that for concretes made with sand and gravel or crushed stone as aggregates. Depending upon the aggregate, the percentages may range from about 40 to 85% at 28 days, and at 6 months or later about 40 to 65%.

Drying Shrinkage

In prestressed-concrete construction, drying shrinkage should be kept to the minimum possible in order to avoid excessive loss of prestress. Shrinkage of concrete is influenced by many factors, most important of which are the amount of water per unit volume of the concrete, the elastic properties of the aggregate, and paste content and characteristics. The size and shape of the member and the type of exposure are factors, but changes in these factors are generally not possible.

In concretes having cement contents in the range of 4 to 6 sk. per cu. yd., the amount of water per unit volume is essentially constant for a particular level of consistency. In mixes richer than about 6 sk. per cu. yd., the amount of water required for the same consistency and workability increases markedly. Rich mixes are generally required for early high-strength concrete. The water content of these mixes can be reduced provided mechanical means of compaction are available. This reduction in water content will result in lower drying shrinkage. This is a particularly effective means of counteracting the inherently higher shrinkage of lightweight-aggregate concretes.

Using the largest maximum size of aggregate that will satisfy placing conditions will result in a lower unit water content and will accordingly, for a particular water-cement ratio, provide more aggregate per unit volume. Aggregate provides considerable restraint to shrinkage of the paste. The more aggregate per unit volume the more restraint to shrinkage. The elastic properties of the aggregate play an important role in drying shrinkage. Those aggregates having a low modulus of elasticity provide less restraint than those of higher modulus; witness the relatively large drying shrinkage of most lightweight-aggregate concretes. Selection of the largest possible maximum size of aggregate having a relatively high modulus of elasticity will result in reduction in drying shrinkage.

High-strength zero-slump concretes generally will show somewhat lower drying shrinkage than the usual structural-grade concrete of plastic consistency. In recent tests(2), concretes made with a natural sand and gravel at a consistency of about $1\frac{1}{2}$ in. slump (2000 to 3500 psi at 7 days) showed an average drying shrinkage at one year of about 680 millionths. For the same aggregate in zero-slump concretes compacted by vibration (6000 to 8000 psi at 7 days) the average drying shrinkage was about 550 millionths. For these two classes of concrete, but made with a typical expanded-shale lightweight aggregate, the respective drying shrinkage averages were 900 and 600 millionths.

Creep

The creep of concrete under sustained load results in a loss in prestress, as does the shortening due to drying shrinkage. Considering this point alone, creep should be kept to a minimum. Creep does serve a useful function, however, in relieving localized overloads by redistribution and equalization of stress.

Most available data indicate that creep of concrete is inversely proportional to its strength. Creep has been related to many other variables such as age, curing, and type of cement. These may be indirect relationships. The physical characteristics of the aggregate are of importance and operate in a manner similar to their effect on drying shrinkage. The moisture content of the concrete is an important factor; concrete which is drying exhibits greater creep than wet concrete.

Many of these means of reducing creep cannot always be utilized. From a practical standpoint, using certain available materials for producing concrete, what are the creep characteristics of high-strength concrete made from these materials? Recent tests(2) of concretes made with natural sand and gravel and with an expanded-shale lightweight aggregate show that the ultimate creep coefficient (millionths per psi) as a function of compressive strength was not linear over the range of strengths from 2000 to 10,000 psi. The relationship departed from linearity at about 5000 to 6000 psi, the higher-strength concretes showing less of a reduction in ultimate creep coefficient with increase in strength than those below 6000 psi. For 7-day loading, at 8000 psi, the ultimate creep coefficient for the sand and gravel concrete was about 0.40 millionths per psi, at 6000 psi it was about 0.55, at 4000 psi 0.80, and at 2000 psi 1.40 millionths per psi. The values for the expanded-shale lightweight-aggregate concretes were about the same at strengths below 5000 to 6000 psi. At the higher strength levels, these concretes showed greater ultimate creep coefficients than the sand and gravel concrete. Most other lightweight aggregates included in this study showed greater creep coefficients at all strength levels than the sand and gravel concrete, while a few showed slightly less creep.

Bond of Concrete to Steel

Bond of concrete to steel increases with increase in compressive strength of the concrete. The relationship is curvilinear, bond strength increasing less rapidly as the compressive strength of the concrete is increased. The bond strengths developed by high-strength concretes are far above the maximum allowable average bond stress recommended by ACI-ASCE Joint Committee 323(6). In some recent tests(2) of vibrated zero-slump concretes in the strength range of 7000 to 10,000 psi, bond strengths of top horizontal bars in pull-out specimens exceeded 1400 psi. Actually, the yield strength of the steel was developed in most of these tests, indicating higher bond strengths than this figure. This was for the sand and gravel concretes and one of the lightweight-aggregate concretes (expanded shale). At the 3000 to 4500-psi level, bond strengths developed for top horizontal bars ranged from 520 to 900 psi. Included in

this latter strength range were seven different lightweight-aggregate concretes and one sand and gravel concrete.

Durability

In many applications, prestressed concrete will be subjected to severe exposure conditions. Bridge decks, for example, will be exposed to the use of salts for purposes of ice removal. Portions of structures may be exposed to freezing and thawing while in a saturated state. These severe service conditions must be met by providing concrete with a high degree of resistance to such exposure.

Water in concrete, like any other water, undergoes about a 9% increase in volume when frozen. This freezing in concrete is a gradual process as the temperature drops because of rate of heat transfer, difference in freezing point of water in the pores of various sizes, and the progressive increase in concentration of dissolved alkalies in the remaining unfrozen paste liquid. Freezing creates an excess volume of water which must reach some relief zone, such as an unsaturated region or an air void, or disruptive hydraulic pressures will be created. Factors which determine the potential destructiveness of this freezing are the amount of water freezing, the permeability of the paste, the tensile strength of the concrete, the rate of freezing, characteristics of the aggregate, and -- most important of all -- the amount and distribution of air voids in the paste.

Based on extensive laboratory data and field service records, we know that the only practical and efficient means of securing a high level of resistance to freezing and thawing is by entraining air in the required amount and proper distribution of air void sizes. In mixes of plastic consistency, the proper amount of air is based on a requirement of $9 \pm 1\%$ of air in the mortar fraction of the mix[8]. For concretes made with aggregate of maximum size $1\frac{1}{2}$ in., the mortar content is approximately 50 to 55% by volume. On a concrete basis, the air content would be $4\frac{1}{2}$ to 5%. For other maximum sizes of aggregate, the required air content would be calculated in the same manner. Control of air is then based on the determinations of the air content of the concrete as a whole.

For the same air-entraining cement or the same amount of air-entraining admixture per unit of cement, decreasing the slump within the range of slumps normally used results in decreased volumes of air entrained. Some laboratory tests made using both a tilting-drum mixer and an open-tub type mixer and a typical Type IA portland cement showed air contents of about $4\frac{1}{2}\%$ at a slump of 3 in., while at a slump of $\frac{1}{4}$ to $\frac{1}{2}$ in. the air content was slightly over 3%. Internal vibration of relatively long duration lowered the air content to about 3% and 2%, respectively. While these are considerable reductions on a volume basis, the resistance to freezing and thawing is primarily dependent on the size and distribution of the air voids, not on the gross amount. Vibration removes the large voids, which account for a greater proportion of the volume of the air, and leaves the average size and spacing of the small, but efficient, voids relatively unchanged.

Curing air-entrained concretes at elevated temperatures does not appear to reduce the beneficial influence of the entrained air on durability. Recent laboratory tests comparing air-entrained concretes made and cured at 70°F and at 105°F indicated comparable resistance to freezing and thawing, even though at the elevated temperature of mixing the volume of air entrained was reduced slightly. In fact, for those concretes whose curing period prior to test included an air-drying period, the 105°F air-entrained concretes were somewhat more durable than the 73°F concretes.

Entrained air increases the durability of concretes made with any of the types of portland cements or portland blast-furnace slag cements. In some recent tests of resistance to scaling[9] resulting from the use of salts for ice-removal purposes, the use of entrained air in concretes made with either Type I, II, or III portland cement produced concretes of comparable and greatly improved resistance to scaling. These particular air-entrained concretes were made by adding an air-entraining admixture at the mixer. Similar results would have been obtained by the use of the respective air-entraining cement types.

Aggregates of good quality are a necessary component of durable concrete. Unsound aggregate particles such as chert, soft sandstone, clay lumps, and some highly absorptive limestones may, when saturated and incorporated in even an air-entrained paste, cause disruption of the concrete during freezing. Some of these aggregates may be beneficiated by drying prior to use or by removal of the offending particles by methods such as heavy-media separation or an elastic-rebound processing technique.

SUMMARY

Early high-strength concrete can be produced by any one of a number of techniques or combinations of techniques. The selection of method will depend upon the availability of specific materials, mixing equipment, and compacting equipment. The following means for obtaining concrete of high quality and having early high

strength for prestressing are suggested, together with other considerations:

1. The use of low water-cement ratio, rich mixes of plastic consistency, or the use of low water-cement ratio, rich, dry mixes placed by mechanical means of compaction such as vibration, to permit the use of more aggregate per unit volume.
2. The use of high-early-strength portland cement (Type III).
3. The use of saturated steam at atmospheric pressure at temperatures below the boiling point of water, together with the use of effective insulation to retain heat generated by cement hydration.
4. Careful control of aggregate gradation, weighing of materials, and mixing, compacting, and curing of concrete.
5. The use of entrained air to assure adequate resistance to exposures involving freezing and thawing and the use of de-icing chemicals.
6. The use of water curing during the early hours of hydration, either by ponding the surface or by the use of saturated aggregates. When dry or saturated lightweight aggregates are used, the provision of additional curing water does not appear necessary since aggregates of this type hold greater amounts of water available for this purpose.
7. Although calcium chloride will increase the early strength development of concrete, in view of the possibility of serious corrosion of the prestressing steel its use in prestressed concrete is not now recommended.

REFERENCES

1. Powers, T. C.: "A Discussion of Cement Hydration in Relation to the Curing of Concrete," Highway Research Board Proceedings Vol. 27, 1947. Reprinted as PCA Bulletin 25.

2. Shideler, Joseph J.: "Lightweight Aggregate Concrete for Structural Applications," to be published in the October 1957 Journal of the American Concrete Institute. Presented at the ACI Convention in Dallas, Feb., 1957.

3. Klieger, Paul: "The Effect of Mixing and Curing Temperature on Concrete Strength," to be published in the Journal of the American Concrete Institute. Presented at the ACI Convention in Dallas, Feb., 1957.

4. Verbeck, George J., and Foster, Cecil W.: "The Long-Time Study of Cement Performance with Special Reference to Heats of Hydration," Proc. ASTM, Vol. 50, 1950. Reprinted as PCA Bulletin 32.

5. "Recommended Practice for Evaluation of Compression Test Results of Field Concrete (ACI 214-57)," Journal of the American Concrete Institute, Proc. Vol. 54, July, 1957.

6. ACI-ASCE Joint Committee 323, "Recommended Practice for Prestressed Concrete," December, 1956.

7. Klieger, Paul: "The Long-Time Study of Cement Performance in Concrete, Chapter 10 - Progress Report on Strength and Elastic Properties of Concrete," to be published in the Journal of the American Concrete Institute.

8. Klieger, Paul: "Effect of Entrained Air on Strength and Durability of Concretes Made With Various Maximum Sizes of Aggregate," Highway Research Board Proceedings, December 1951. Reprinted as PCA Bulletin 40.

9. Klieger, Paul: "Curing Requirements for Scale Resistance of Concrete," Highway Research Board Bulletin 128, 1956. Reprinted as PCA Bulletin 82.

SELECTED BIBLIOGRAPHY

Banks, R. R.: "High Strength Concrete Required for Prestressing," Commonwealth Engr. 41, (2) 48-51 (Sept. 1953); Abstract in Eng. Ind. (1953).

Banks, K. R.: "High Strength Concrete for Prestressing," Constructional Review 26, (3) 17-25 (1953); Abstract in B. S. A. 26 (9) 1145 (Sept. 1953).

Banks, K. R.: "High Strength Concrete for Prestressing," Symposium on Prestressed Concrete, Sydney, June 30 - July 2, 1953, Cement and Concrete Assoc. of Australia, pages 40-47; discussion, pages 48-54.

Blanks, R. F.: "Concrete for Prestressing," First U. S. Conference on Prestressed Concrete (see B. S. A. 1538) 136-49 (1951); Abstract in B. S. A. 24 (12) 1671 (Dec. 1951).

Carlson, R. W.: "Drying Shrinkage of Concrete as Affected by Many Factors," Proc. ASTM, Vol. 38, Part II, 1938.

Collins, A.R.: "The Principles of Making High-Strength Concrete," Engineering 169 (4382) 80-1 (Jan. 20, 1950).

Davis, R.E. and Troxell, G.E.: "Properties of Concrete and Their Influence on Prestress Design," Journal of the American Concrete Institute, January, 1954, (Proc. Vol. 50).

Kennedy, H.L.: "High Strength Concrete," First U.S. Conference on Prestressed Concrete (see B.S.A. 1538) 126-35 (1951); Abstract in B.S.A. 24 (12) 1670 (Dec. 1951).

Menzel, Carl A.: "An Investigation of Bond, Anchorage, and Related Factors in Reinforced Concrete Beams," Portland Cement Association, Research Department Bulletin No. 42.

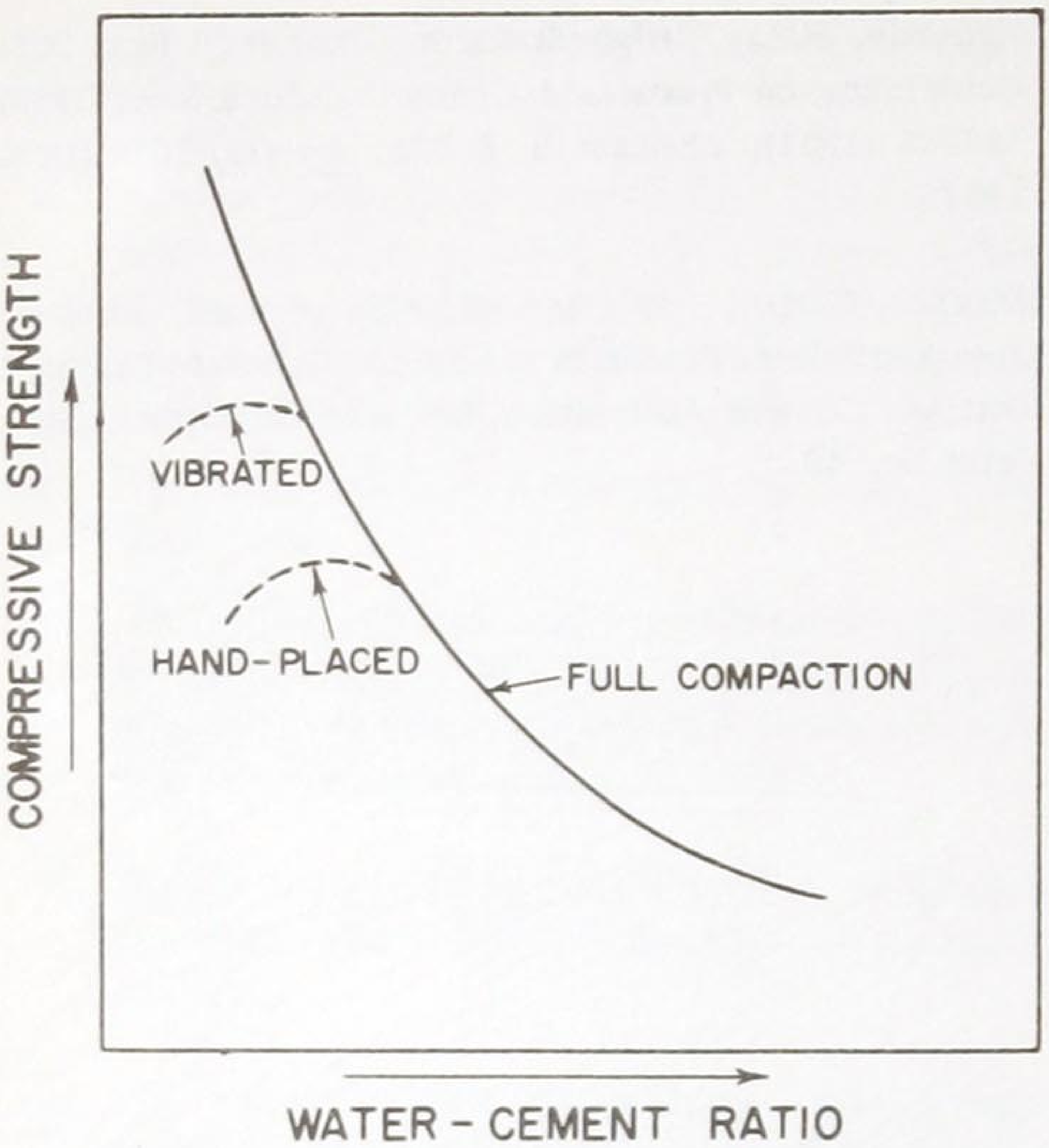

Fig. 1 Influence of W/C on Strength

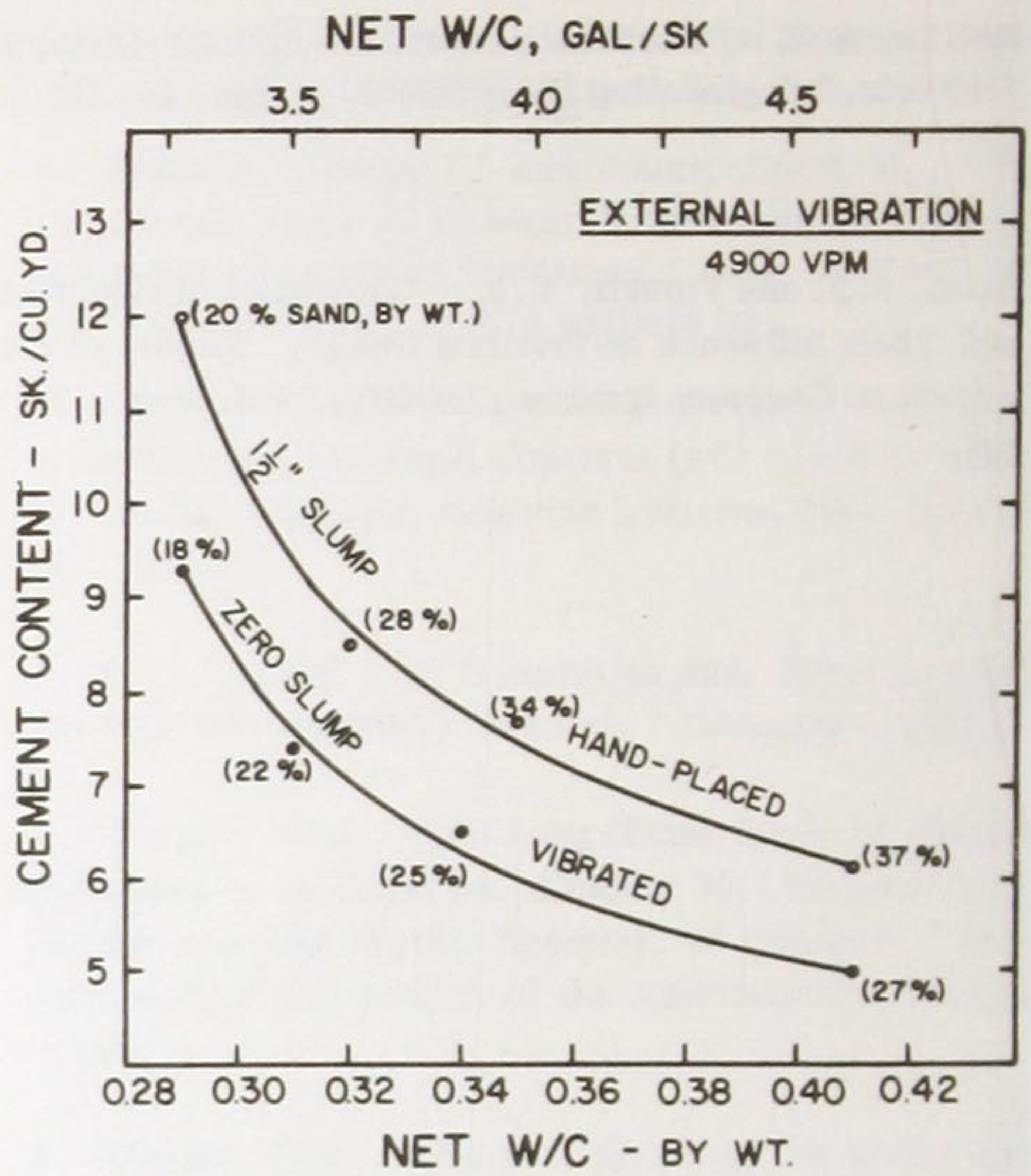

Fig. 2 Influence of Method of Compaction on Cement Requirements

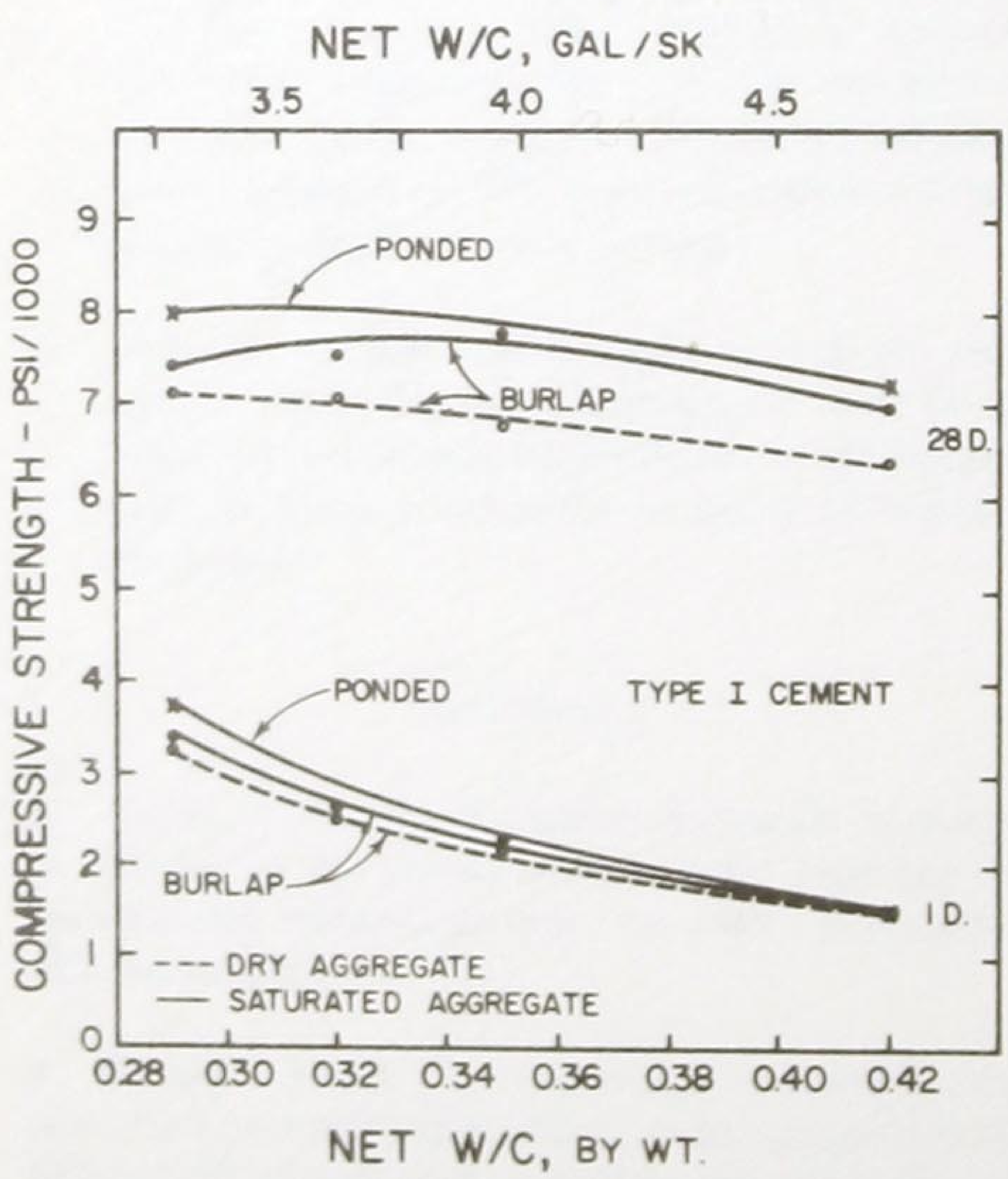

Fig. 3 Influence of Moisture Availability on Strength Development (Hand-Placed Concretes)

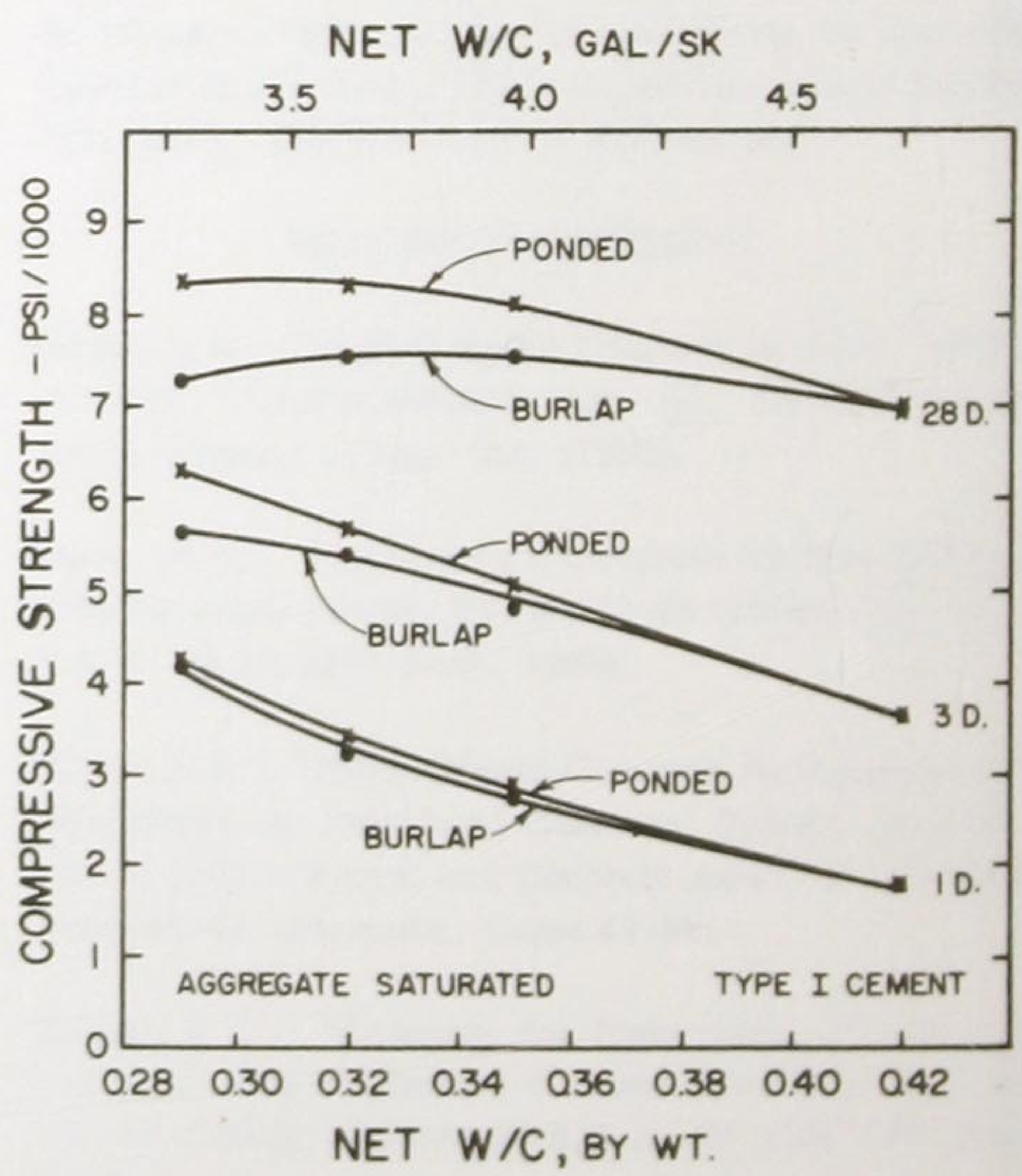

Fig. 4 Influence of Moisture Availability on Strength Development (Vibrated Concretes)

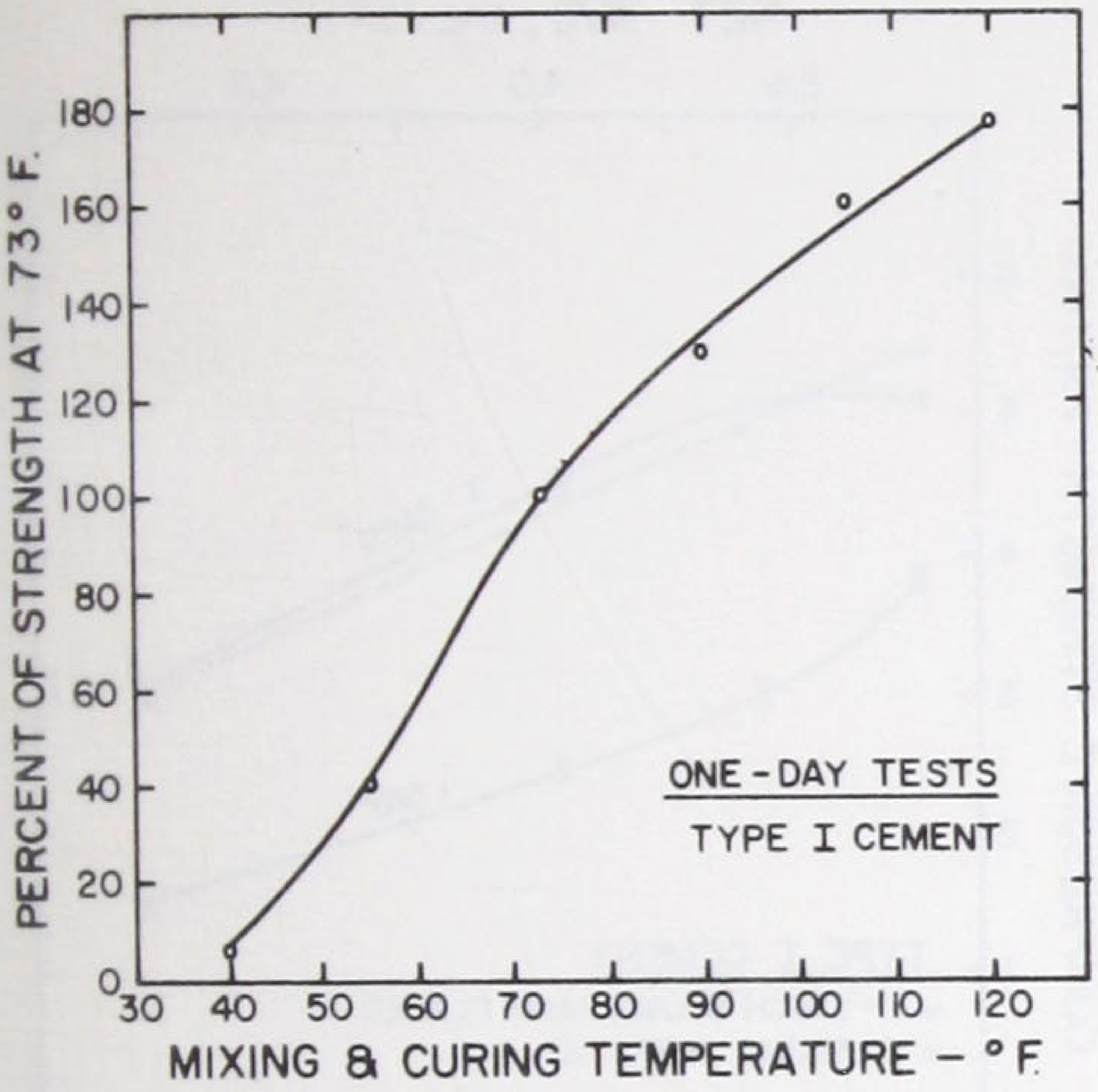

Fig. 5 Influence of Mixing and Curing Temperature on Early Strength Development

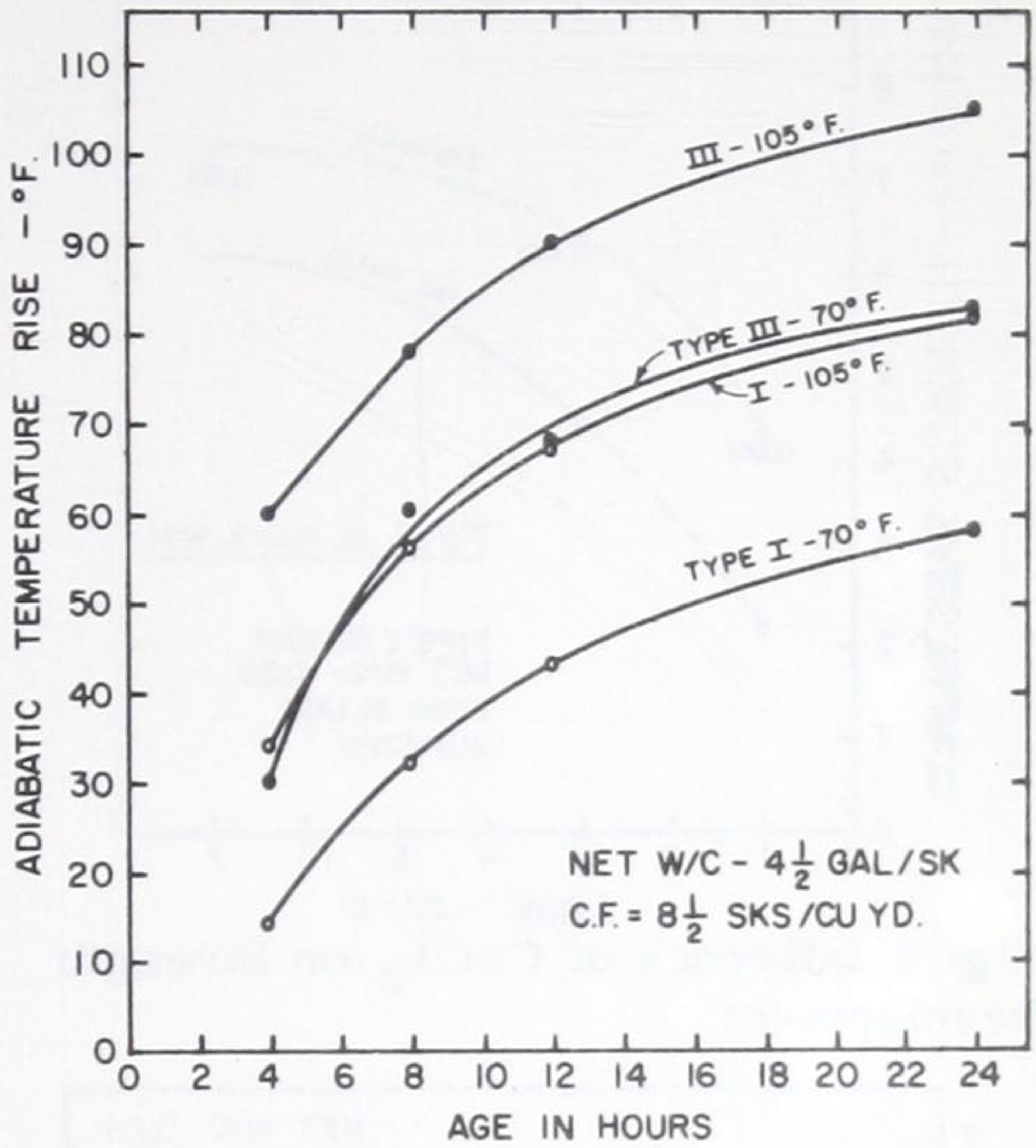

Fig. 6 Influence of Heat Generated During Hydration on Concrete Temperature (Calculated Assuming Full Retention of Heat Generated)

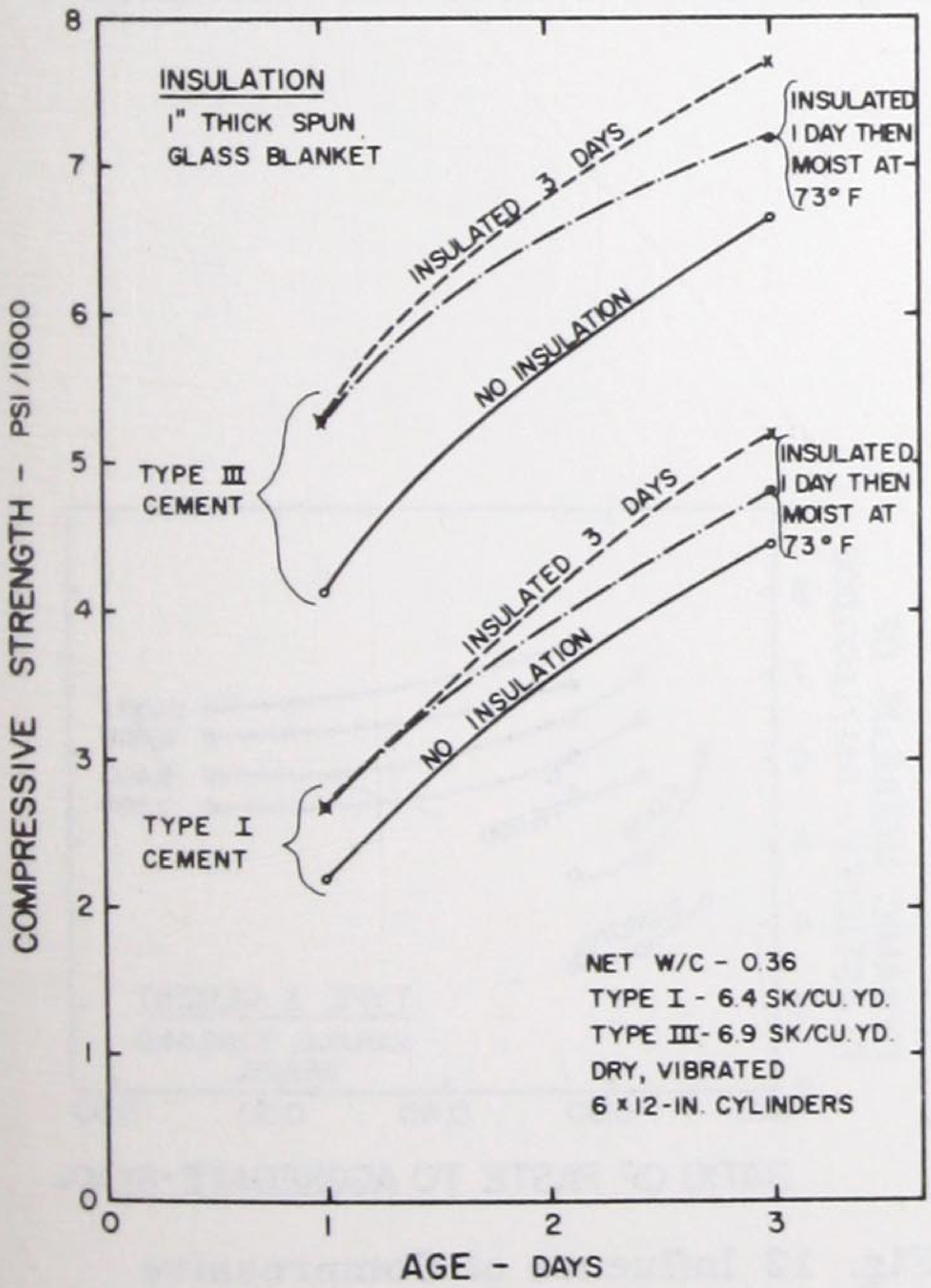

Fig. 7 Influence of Heat Insulation on Strength Development

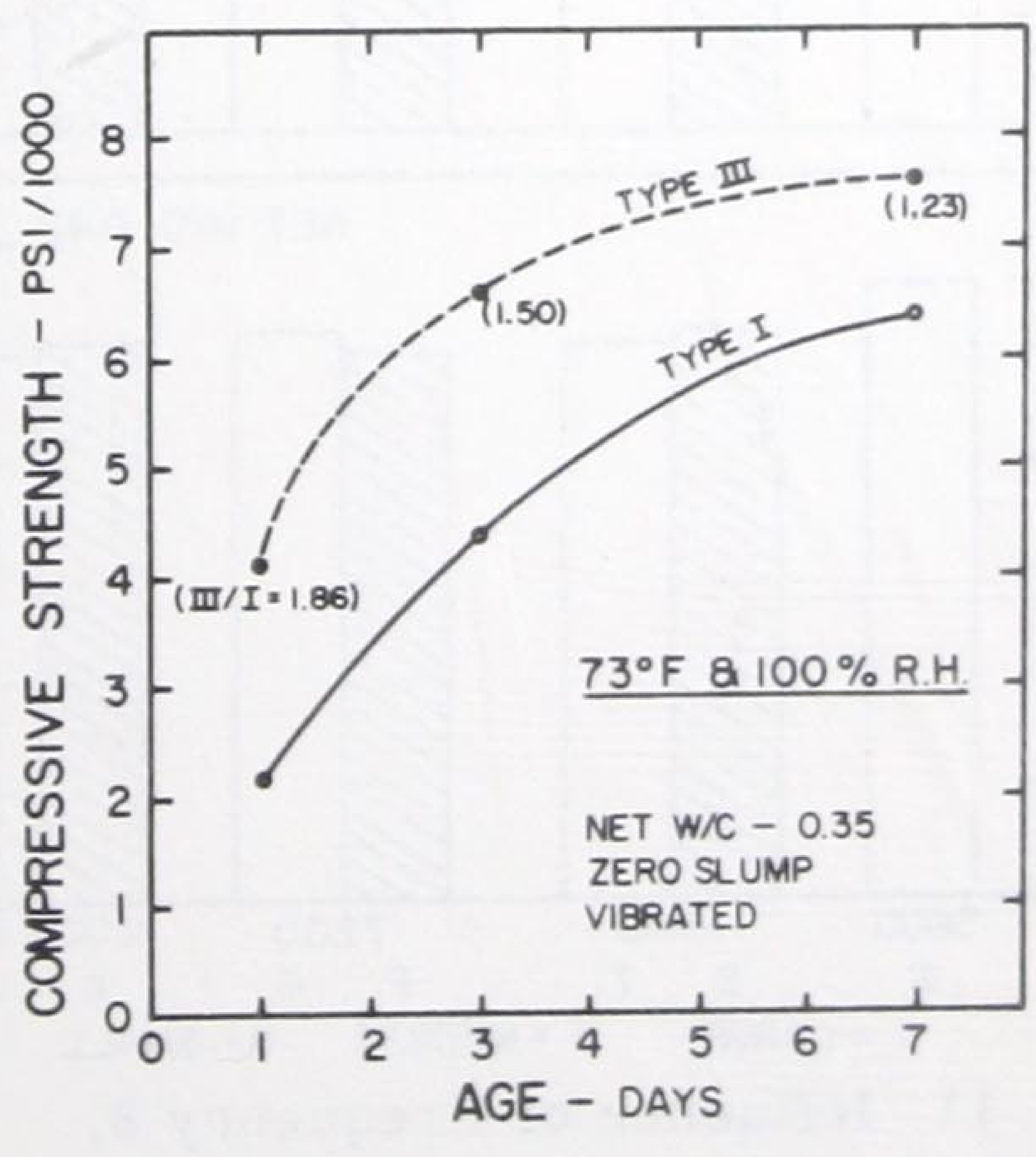

Fig. 8 Influence of Cement Type on Strength

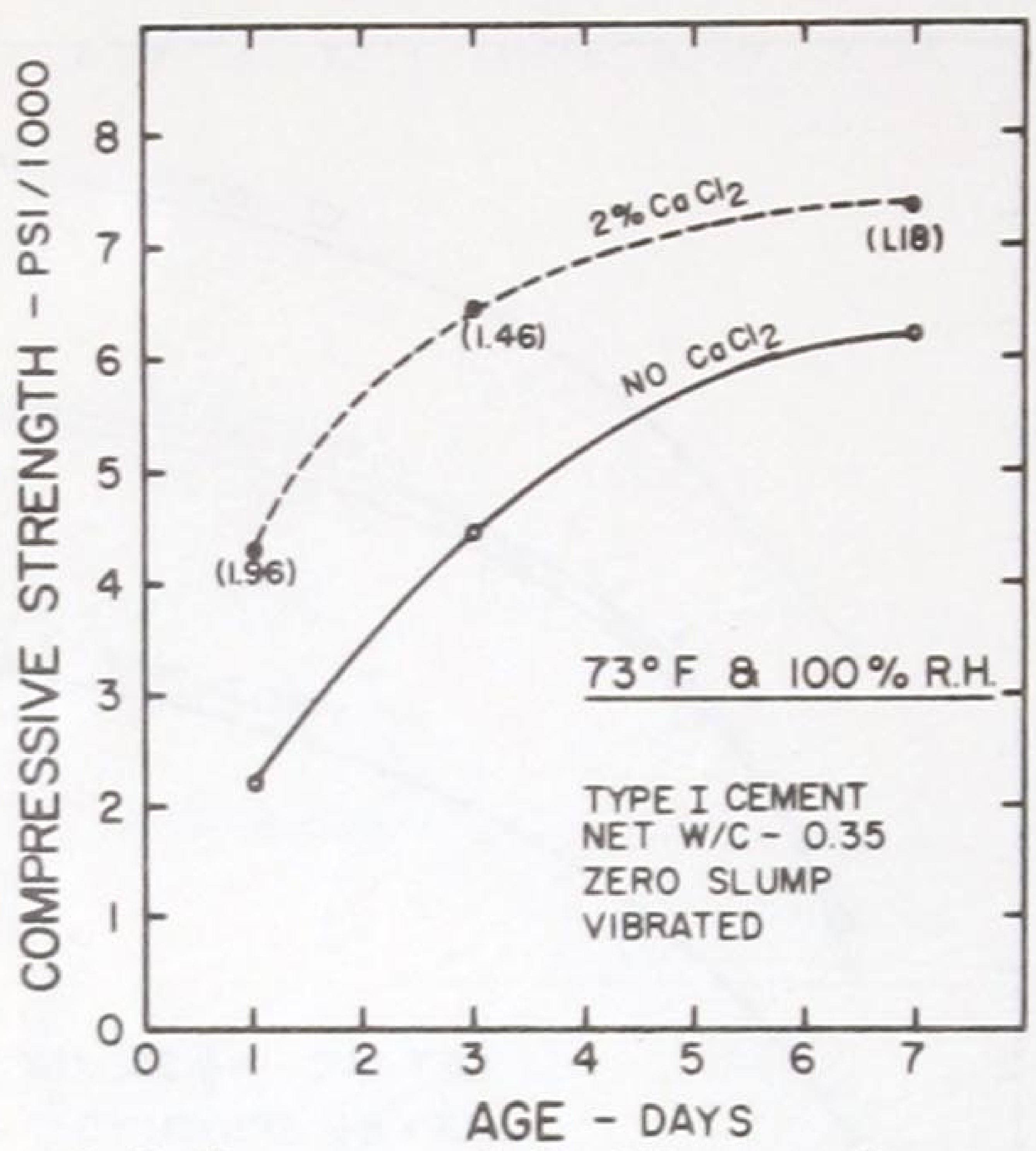

Fig. 9 Influence of $CaC1_2$ on Strength Development

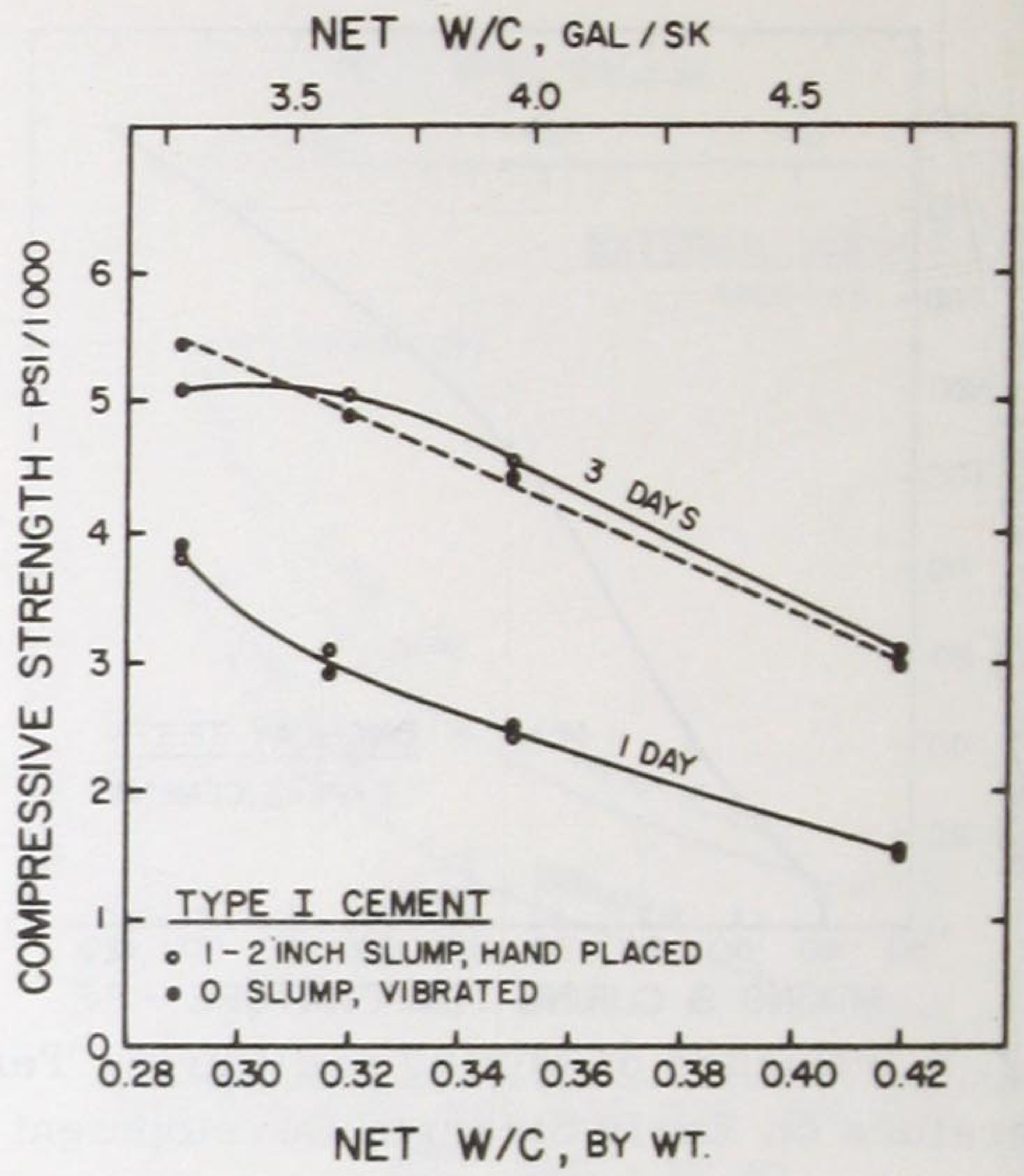

Fig. 10 Hand-Placed vs. Vibration

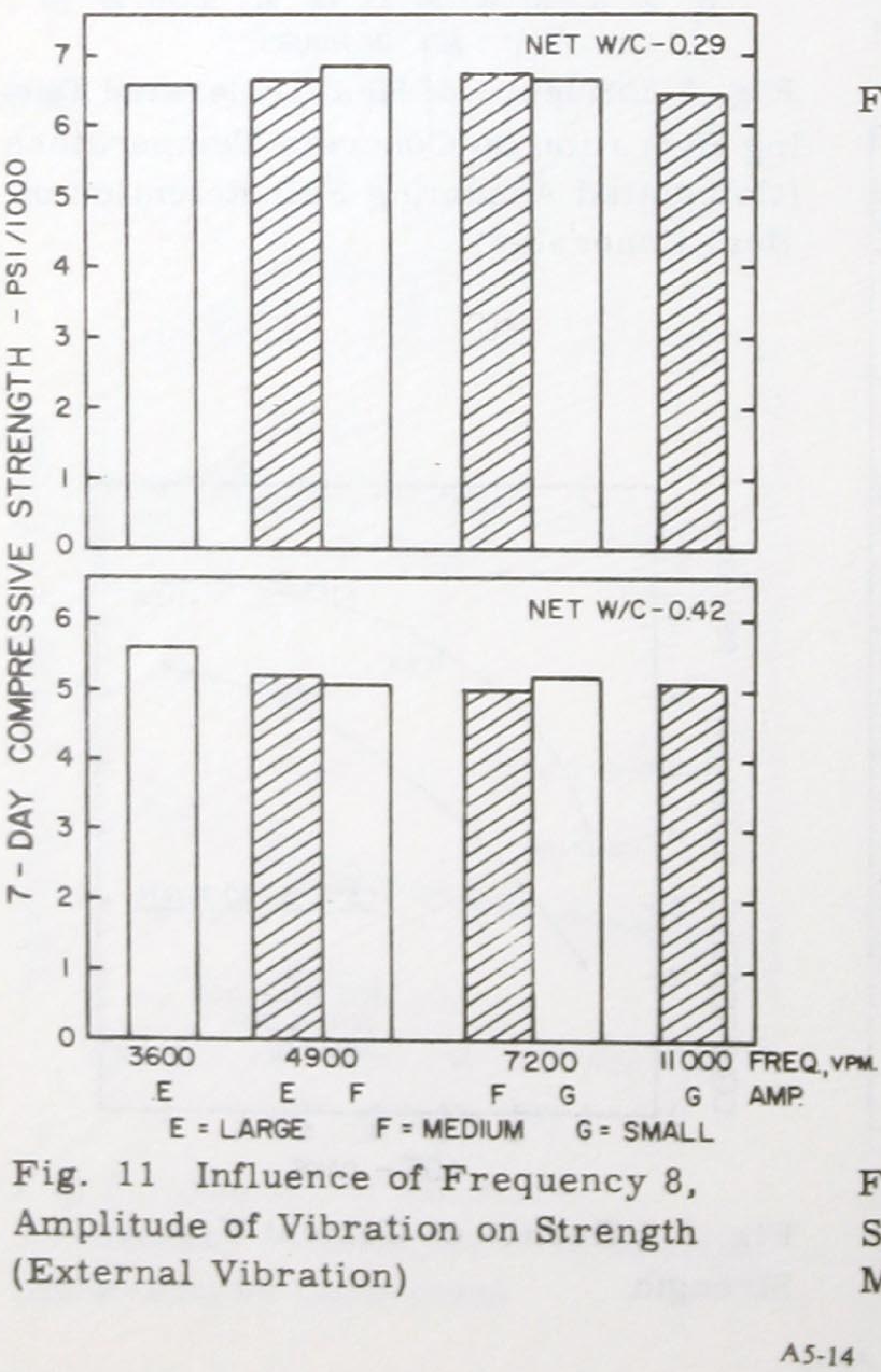

Fig. 11 Influence of Frequency 8, Amplitude of Vibration on Strength (External Vibration)

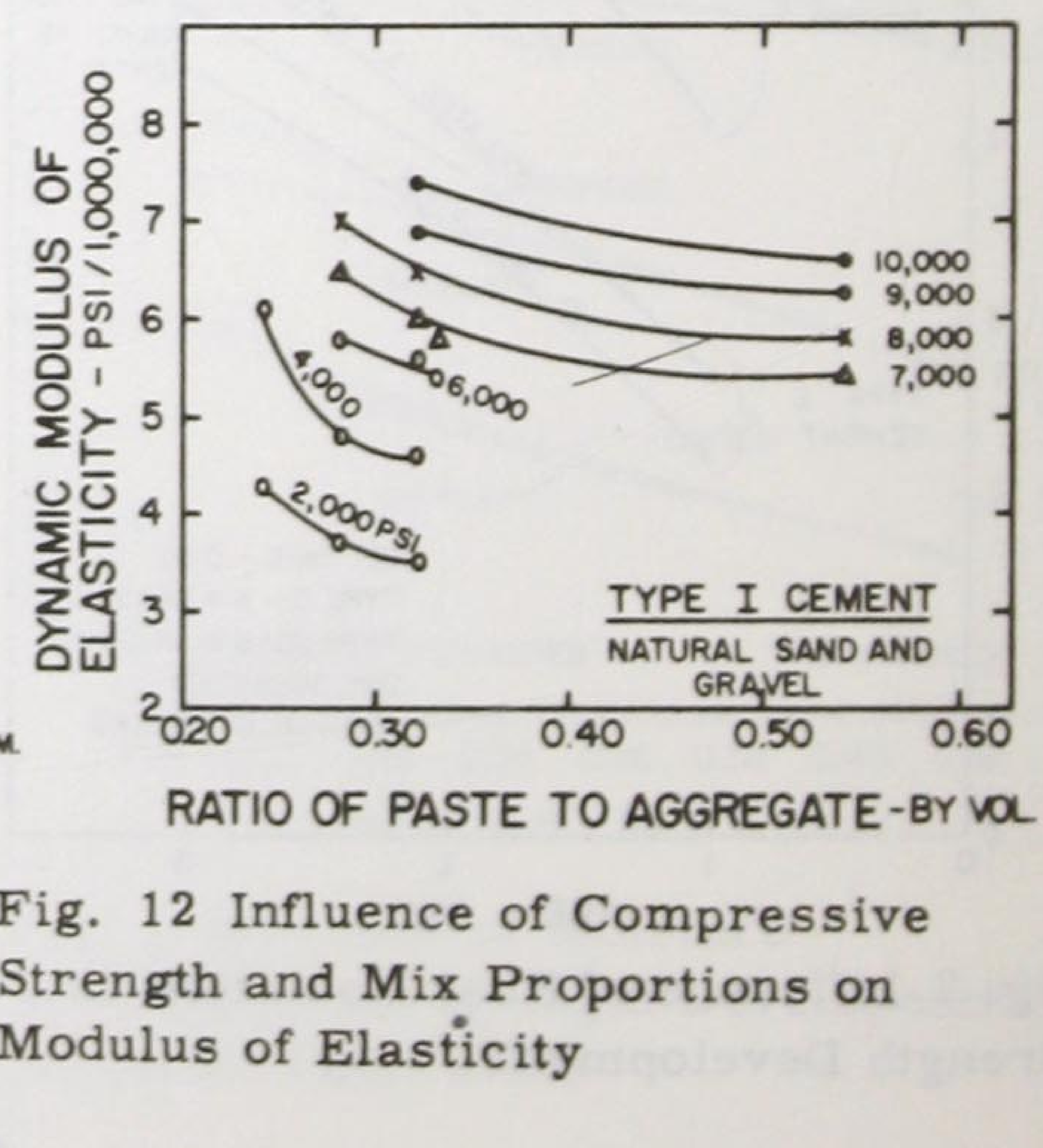

Fig. 12 Influence of Compressive Strength and Mix Proportions on Modulus of Elasticity